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Requirements for True Time Delay Imaging Systems with Photonic Components

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Abstract

In this paper, we generalize the phase and amplitude requirements of microwave components, within true time delay imaging systems, to include photonic devices. An analytic expression for the relationship between the optical and RF transfer functions is suggested for double sideband modulation and the effect of optical phase ripple on RF transfer function is simulated for an optical component such as a chirped Bragg grating. The effect of phase ripple on the system impulse response is considered.

1.0 Introduction

The newest generation of imaging systems is expected to have wide bandwidth and cover a wide sector of scan. These criteria can be met by phased array radar with an electrically large, true time delay antenna. However, besides the construction of an efficient T/R module, other major challenges arise [1]. They include the large number of switchable true time delays on the level of subarrays and the need for equidistant path lengths. Tracking radars which have an instantaneous narrow bandwidth can be calibrated with the systems phase shifters and attenuators, but imaging systems which use a chirped pulse (LFM) waveform [1], having a wide equivalent instantaneous wide bandwidth, need to maintain calibration over the entire frequency range. Therefore, the components, both RF and optical, used in the system should have almost constant group delay as a function of frequency to prevent distortion of the wideband LFM pulse. The most common solutions until now for true time delay have been either a lens or a matrix of cables [2]. Both solutions are bulky and add weight. In receive, the more futuristic solution is heading towards digital beamforming with a wideband receiver on each subarray [3]. An attractive solution to the problem of true time delay in transmit is a photonic based beamformer, typically using dispersive devices (Fig. 1) [4, 5]. However, dispersion and its wavelength dependence may limit the performance of LFM systems. While several papers have analyzed the deleterious effects of 1st order dispersion, their analyses concentrate on CW waveforms [6]. Previous work has also been done on measuring the optical dispersion of these photonic components, but without relating these measurements to the RF processing [7].

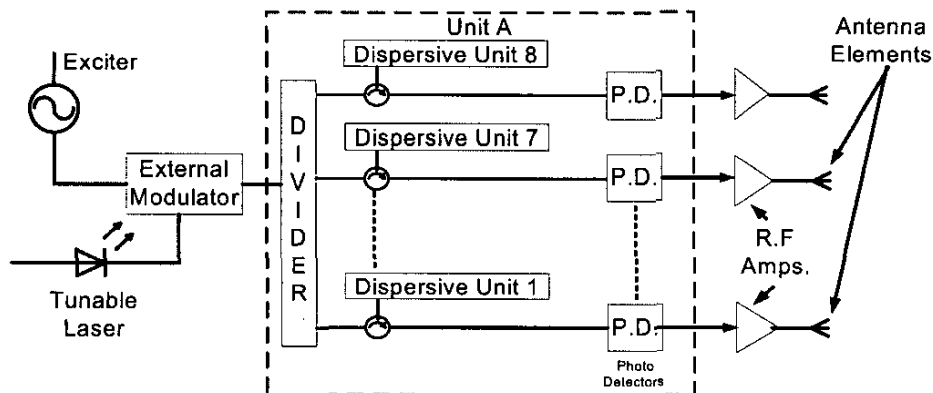


Figure 1: Photonic Beamformer with Dispersive Units

The dispersive device in the beamformer of Figure 1 has been implemented in various ways such as

- a.) Dispersive fibers (including HOM fibers) [8]
- b.) Chirped Bragg gratings [7,9]
- c.) WDM and AWG switched line device [10]

For future systems, we have evaluated the above in terms of volume, weight, stability with temperature and electrical performance. This paper relates to the special electrical requirements for wideband LFM systems.

2.0 Phase and Amplitude Requirements

Within the wideband LFM imaging system are several types of errors that have various effects on the system. When the LFM imaging system incorporates a phased array, the analysis is more complex. The paths between each element in the phased array and the transmitter/receiver can be thought of as individual channels. Each channel has its own electrical properties, which vary as a function of scan angle. These properties will affect both the spatial antenna pattern and the temporal impulse response function of the imaging system. It is possible to find a transfer function to represent the frequency response of each channel. The imaging system impulse response is a summation of the impulse responses of all the channels, while the wideband spatial antenna pattern is a weighted function of the antenna pattern at all frequencies within the instantaneous bandwidth. These considerations translate to requirements on what the transfer function for either an RF, photonic or digital beamformer can be within an imaging systems—typically with allowed deviations of 2-3 picoseconds in group delay [5]. This tolerance is necessary to maintain high resolution (beamwidth of the impulse response) and a good contrast in the picture (low ISLR). For instance, in photonic true time delay (TTD) systems, it is common to use highly dispersive chirped Bragg gratings to create delay lines with time delays varying according to the optical carrier. However, these Bragg gratings can cause both amplitude fading if the dispersion is large enough [4]. More importantly, their group delay ripple in the optical region will affect the RF transfer function. This study looks at the deleterious effect of this group delay ripple on LFM systems and suggests and measures alternatives such as WDM components.

3.0 Photonics –Theory

To study these effects, the following setup was studied both theoretically and experimentally (Fig 2). A laser sends a CW optical signal of optical frequency ω_c to a quadrature-biased external Mach-Zender modulator, which is excited by a wideband LFM pulse. The output E-field, which is a function of the modulation index, now goes through an optical filter or dispersive medium, which has an optical transfer function $H(\omega)$. The output lightwave is directly detected by the photodiode and produces an RF signal, which is proportional to the input optical intensity. This signal serves as the input to the imaging system, where, using a dechirp method [1], it is correlated with the original signal from the RF exciter, generating the required information.

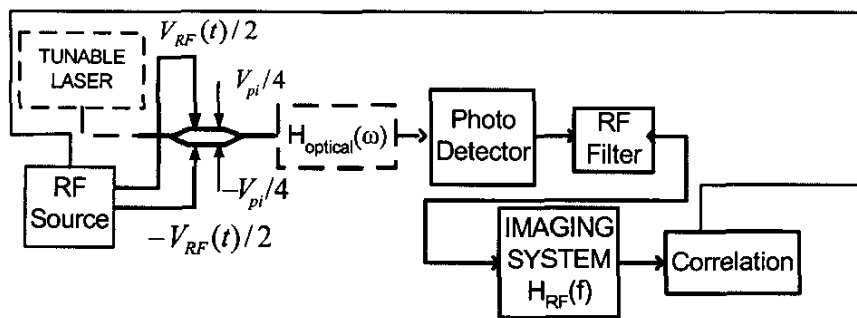


Figure 2: Schematic of an Optical Device, Integrated with the Imaging System

First, it is worthwhile looking at what happens for a small modulation index and a single tone RF signal of the form $\cos(\omega_{RF}t)$. Assuming double sideband modulation (DSB) and no phase noise, the E-field at the modulator output is

given by $E_1(t) = C \exp[j\omega_c t] \left[1 - K_1 (\exp[j\omega_{RF} t] + \exp[-j\omega_{RF} t]) \right]$ [6]. This optical signal comprises three optical frequencies:

$$E_1(t) = C \exp[j\omega_c t] - K_2 \exp[j(\omega_c + \omega_{RF})t] - K_2 \exp[j(\omega_c - \omega_{RF})t] \quad (1)$$

For a linear dispersive optical beamformer of the form $H(\omega) = \exp[-j\varphi(\omega)]$ [6], the E-field at the photodiode input is:

$$E_{Det}(t) = C \exp[j(\omega_c t - \varphi(\omega_c))] \left[1 - K_1 \exp[j(\omega_{RF} t - \Delta\varphi^+(\omega_{RF}))] - K_1 \exp[-j(\omega_{RF} t - \Delta\varphi^-(\omega_{RF}))] \right] \quad (2)$$

where: $\Delta\varphi^+(\omega_{RF}) = \varphi(\omega_c + \omega_{RF}) - \varphi(\omega_c)$; $\Delta\varphi^-(\omega_{RF}) = \varphi(\omega_c) - \varphi(\omega_c - \omega_{RF})$.

The detector current is proportional to the optical intensity

$$I(t) = |E(t)|^2 = C_2 \left[1 - K_3 \cos\left(\frac{\Delta\varphi^+ - \Delta\varphi^-}{2}\right) \cdot \cos(\omega_{RF} t - (\Delta\varphi^+ + \Delta\varphi^-)/2) \right] \\ = C_2 \left[1 - K_3 \cos(\Phi_{amp}(\omega_{RF})) \cdot \cos(\omega_{RF} t - \Phi_{phase}(\omega_{RF})) \right] \quad (3)$$

where:

$$\Phi_{amp}(\omega_{RF}) = (\varphi(\omega_c + \omega_{RF}) + \varphi(\omega_c - \omega_{RF}) - 2\varphi(\omega_c))/2 \\ \Phi_{phase}(\omega_{RF}) = (\varphi(\omega_c + \omega_{RF}) - \varphi(\omega_c - \omega_{RF}))/2 \quad (4)$$

We have thus retrieved the original RF signal but with frequency-dependent amplitude and phase. Since

$$\varphi(\omega_c + \omega') = \varphi(\omega_c) + \left. \frac{d\varphi}{d\omega} \right|_{\omega_c} \omega' + \left. \frac{1}{2} \frac{d^2\varphi}{d\omega^2} \right|_{\omega_c} (\omega')^2 + \left. \frac{1}{6} \frac{d^3\varphi}{d\omega^3} \right|_{\omega_c} (\omega')^3 + \dots \quad (5)$$

and in view of Eq. (4), it is clear that even derivatives of the optical phase of the transfer function affect the amplitude of the intensity, while odd derivatives of the optical phase of the transfer function affect its phase. For the well studied case of constant dispersion, $d^n\varphi/d\omega^n|_{\omega_c} = 0, \forall n > 2$,

$$I(t) = C_2 \left[1 + K_2 \cos(\varphi''(\omega_c) \omega_{RF}^2 / 2) \cdot \cos(\omega_{RF} t - \varphi'(\omega_c)) \right], \quad (6)$$

representing a signal with a constant phase but frequency-dependent amplitude, which can go to zero when $\varphi''(\omega_c) \omega_{RF}^2 / 2 = \pi / 2$. For double sideband modulation, this sets an obvious upper limit as to how dispersive the optical system used in the imaging system can be. However, for the general case, where the dispersion itself, $d^2\varphi(\omega)/d\omega^2$, is frequency dependent, both amplitude and phase distortion are important to LFM systems.

A chirped RF pulse can be expressed as $x(t) = \text{Re}\{\exp[j(\omega_{RFc} t + \alpha t^2)]\}$ for $-T/2 < t < T/2$. Decomposing it into its Fourier spectrum, we find

$$x(t) = \frac{1}{2} \left[\int_{-\infty}^{\infty} C(\omega) \exp[-j\omega t] d\omega + \text{complex conjugate} \right], \quad (7)$$

where $C(\omega)$ is a complex weighting function, which has a parabolic phase for an undistorted chirped pulse [1].

Feeding this signal into the modulator and using some simplifying assumptions, one can generalize Eq. (6) to obtain an expression for the RF components of interest ($\omega_{RFc} - \alpha T < \omega < \omega_{RFc} + \alpha T$) in the optical intensity at the detector input,

$$I(t) \Big|_{\omega_{RFc} - \alpha T < \omega < \omega_{RFc} + \alpha T} \approx \text{Re} \left\{ \int C(\omega) \cos(\Phi_{amp}(\omega)) \cdot \cos(\omega t - \Phi_{phase}(\omega)) d\omega \right\} \\ \approx \text{Re} \left\{ \int [C(\omega) \exp[j\Phi_{phase}(\omega)] \cos(\Phi_{amp}(\omega))] \cdot \exp[j\omega t] d\omega \right\} \quad (8)$$

The intensity is a weighted superposition of intensities of instantaneous CW frequencies, with frequency-dependent amplitude and phase distortions, originated from the optical system. In the dechirping processing of the LFM signal, these errors will affect the output temporal impulse response: slow fluctuations of the phase error (with respect to the pulse bandwidth) will broaden the impulse response, while fast fluctuations will raise its sidelobes. As shown in [1], the phase error of a periodic perturbation must be less than 7 degrees peak to peak in order for the peak sidelobes of the temporal impulse response to remain under 25 dB. This sets a limitation on using components with fluctuating dispersion, such as the sinusoidal group delays found in Bragg gratings [8]. Amplitude errors have a less severe effect on the impulse response and might be corrected using equalizers. Note that single side band modulation, while removing the limitations imposed by constant dispersion [6], will not solve the problem of group delay ripple.

4.0 Simulation

To achieve high signal-to-noise ratio, the modulator will employ a large modulation index, resulting in a non-linear response so that a numerical simulation is required. This has been done in a general way, including accurate modeling of the modulator and the optical channel, as well as dechirping.

As an example, a DSB optical link incorporating a chirped Bragg grating with a sinusoidal group delay of 5 picoseconds and a period of $0.25 \cdot \text{Bandwidth}$ was simulated. The modulation index was 0.1, and the signal of interest is contained in the bandwidth F_L to F_H . The phase and amplitude errors relative to an ideal LFM pulse were calculated (Figs.3-4). The distorted signal is then correlated with the initial LFM pulse and compared to the ideal impulse response. As is shown in Fig. 5, the phase errors raise the sidelobes of the impulse response by over 10 dB. This is not acceptable for most high resolution systems.

5.0 Measurements

The setup of Fig. 1 has been constructed with both a WDM demultiplexer and fibers of various lengths and with HOM (higher order mode) fiber to implement a discrete true time delay circuit. Using a network analyzer to measure the RF S-parameters as a function of frequency, and after calibration relative to the optical link without the dispersive subsystem, measurements were taken over the frequency band of the 4.5-5.5 GHz. For delays from 5 to 1000 picoseconds, phase ripple less than 0.5 degree were obtained with the HOM fiber and phase ripple less than 1 degree was obtained with the WDM topology, values which are significantly lower than those obtained for fiber Bragg gratings in the literature. Both topologies appear suitable for most LFM applications. However, the WDM topology has an advantage under environmental harsh conditions as it demands much shorter lengths of fiber.

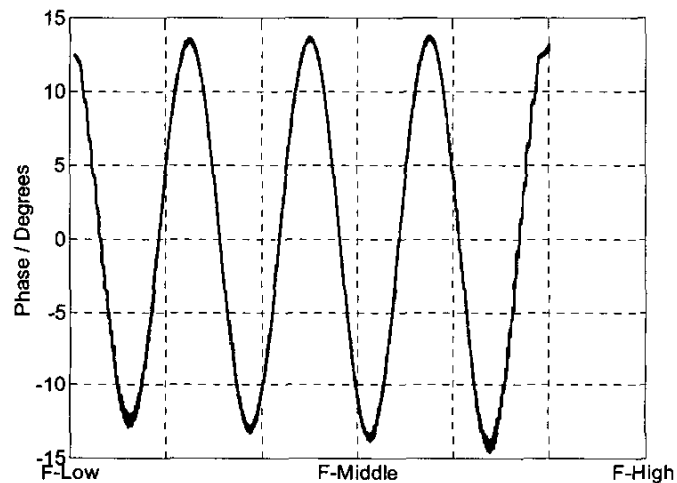


Figure 3: RF Phase Error after Detection

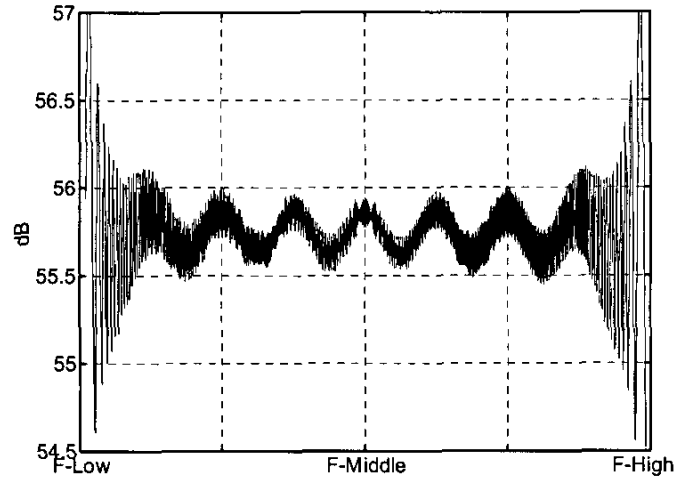


Figure 4: RF Amplitude Error after Detection

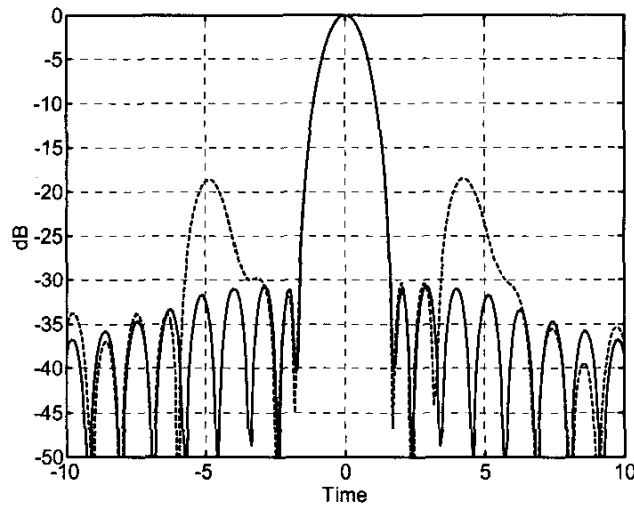


Figure 5: Ideal Impulse Response Function (Solid Line) vs. Impulse Response Function after Optics (Dotted Line)

Summary

The most recent advances of photonic components may soon allow inclusion within radar systems of complex waveforms. The magnitude and shape of the optical dispersion can be a determining factor as to which optical topologies can be used without fatally distorting the RF pulse. New photonic techniques for photonic TTD promise to provide RF transfer functions free of phase ripples.

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